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Analysis of the optoacoustic signals generated with a tone-burst of nanosecond duration pulses

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ABSTRACT

Biomedical optoacoustic (photoacoustic) imaging is generally performed with short laser pulses with durations in the order of a few nanoseconds. This enables maximizing the conversion efficiency of optical energy into acoustic (ultrasound) energy when light is absorbed in biological tissues. The generated ultrasound waves are generally very broadband, with typical frequency spectra ranging from tens of kHz to tens of MHz. Most ultrasound transducers used for the detection of optoacoustic signals have a finite detection bandwidth, in a way that they are not optimal for the acquisition of optoacoustic signals generated with a single pulse. In this work, we analyze a narrowband excitation approach based on a tone-burst consisting of multiple equally-delayed short pulses. We compare the power spectral density of the signals generated with a tone-burst with those generated with a single pulse having the same energy under safety exposure limits. We further analyze the performance of tone-burst excitation when non-linear effects take place. Specifically, we consider non-linearities associated to temperature increase and to optical absorption saturation.

Keywords: Optoacoustic imaging; Narrowband excitation; Tone-burst excitation; Signal-to-noise ratio

1. INTRODUCTION

Optoacoustic (photoacoustic) imaging of biological tissues is based on pressure signals thermoelastically generated by absorption of modulated light. The conversion efficiency of optical to acoustic energy is generally low and is maximized for sharp variations of light intensity [1]. Therefore, short pulsed lasers on nanosecond-range timescales are typically used in biomedical optoacoustics [2]. The energy of the pulse depends on the target depth. Thus, while <1 µJ pulses are used in optical-resolution microscopy for depths shallower than 1 mm, pulse energies in the mJ to tens of mJ range are needed to provide sufficient contrast at deeper regions [3].

The bandwidth of the collected optoacoustic signals depends on several factors such as the temporal duration of the laser pulse, the shape and dimensions of the absorbing structures generating the signals, acoustic attenuation and the frequency response of the ultrasound detector(s) [1,4,5]. Although broadband detectors e.g. based on optical interferometers are available [6,7,8], piezoelectric sensors remain the workhorse in optoacoustic imaging due to their superior sensitivity and robustness. Most piezoelectric transducers have limited bandwidth and hence represent an inefficient approach to collect broadband optoacoustic signals, even when combining multiple sensors [9]. More narrowband excitation of optoacoustic signals can be achieved with low-power intensity modulated laser sources. For this, intensity modulation methods based on a sinusoidal, chirped or sinusoidal-burst functions have been suggested [10,11,12]. Intensity modulated light sources generally represent a less expensive approach than short-pulsed lasers. However, the signal-to-noise ratio (SNR) of the signals is orders of magnitude lower than that obtained with pulsed excitation [13]. Herein, we describe an alternative narrowband optoacoustic excitation approach based on a tone-burst consisting of a train of equally-delayed short pulses.

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Several cases are described where the signal-to-noise ratio (SNR) of the signals generated with this approach can potentially be higher than for single pulse excitation. A more detailed description is provided elsewhere [14].

2. LINEAR OPTOACOUSTIC REGIME

For laser pulse durations below the acoustic and thermal confinement times, the wave equation that describes the pressure field $p_N(x,t)$ generated by a tone-burst consisting of *N* pulses separated by Δt can be expressed as [1]

$$\frac{\partial^2 p_N(x,t)}{\partial t^2} - c^2\nabla^2 p_N(x,t) = \Gamma H(x) \sum_{n=0}^{N-1} \frac{\partial\delta(t-n\Delta t)}{\delta t}, \qquad (1)$$

where *c* is the speed of sound, Γ is the dimensionless Grueneisen parameter and *H*(*x*) is the absorbed energy per unit volume and per pulse. The solution of Eq. (1) is given by

$$p_N(x,t) = \frac{1}{N}\sum_{n=1}^{N-1} p_1(x, t - n\Delta t), \qquad (2)$$

being $p_1(x,t)$ the pressure wave field generated with a single pulse with the same optical energy as the burst, which can be expressed as [15]

$$p_1(x,t) = \frac{\Gamma}{4\pi c}\frac{\partial}{\partial t}\int_{S'(x,t)} \frac{H(x')}{|x-x'|} dS'(x,t), \qquad (3)$$

Eq. (3) can be analytically solved for some geometries [1]. For example, a spherical absorber emits the characteristic *N*-shape signals depicted in Fig. 1a for single-pulse excitation (blue) and for a tone-burst consisting of 3 pulses (red). Without loss of generality, the pulse repetition frequency of the bursts was selected to match the peak of the frequency spectrum of the signals generated by the sphere with a single pulse. Fig. 1b displays the frequency spectra of the pressure signals shown in Fig. 1a. It is shown that the amplitude spectral density of the signals generated with a tone-burst is always lower or equal than that of the signals generated for single pulse, being equal only for the pulse repetition frequency of the burst and subsequent harmonics. This indicates that the energy of the signals, and hence the SNR, is higher for single pulse excitation in the linear optoacoustic regime. On the other hand, tone-burst excitation leads to a reduction of the bandwidth of the generated signals. The full-width at half maximum (FWHM) measured in the spectra of the signals is plotted in Fig 1c as a function of the number of pulses of the burst. Note that for *N*=1, the FWHM is determined by the diameter of the sphere.

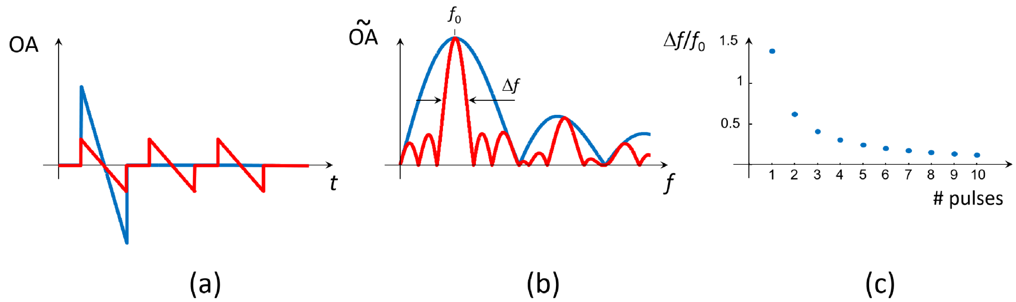

Figure 1: Comparison of the optoacoustic signals generated by a spherical absorber with single-pulse and tone-burst (3 pulses) excitation in the linear optoacoustic regime. The pulse repetition frequency of the bursts was selected to match the peak of the frequency spectrum of the signals generated by the sphere with a single pulse (a) Time profiles of the pressure signals for single-pulse (blue) and tone-burst (red) excitation. (b) Amplitude of the Fourier transforms of the profiles in (a). (c) Relative bandwidth of the optoacoustic signals generated with a tone-burst as a function of the number of pulses of the burst.

An important issue to consider, particularly if optoacoustics is translated into the clinics, is to ensure that no tissue damage is produced due to laser exposure. The maximum optical energy that can be delivered into a tissue is established by safety exposure standards [16]. Specifically, the maximum energy density Φ_{max} in mJ/cm^2 at the tissue surface is given by

$$\Phi_{max} = \begin{cases} 20C_A \ if\ T_{exp} \leq 10^{-7}s \\ 1100C_A{T_{exp}}^{0.25}\ if\ T_{exp} > 10^{-7}s' \end{cases} \quad (4)$$

where T_{exp} is the exposure time and C_A is a factor that depends on the optical wavelength. $T_{exp}<10^{-7}$s for a single laser pulse with typical nanosecond durations. However, T_{exp} is larger when exciting the tissue with a tone-burst. Then, even though the energy conversion efficiency is lower than for single-pulse excitation, the fact that more energy can be delivered when conforming to safety standards can lead to a higher SNR of the signals in some cases, particularly for tone-bursts with relatively low pulse repetition frequency.

3. NON-LINEAR EFFECTS

The optoacoustic signal generation mechanism can change if non-linear effects take place. Herein, we describe the effects of two non-linearities in the generated optoacoustic signals with a single pulse and with a tone-burst of short pulses, namely optical absorption saturation and temperature rise in the tissue. Since in the linear optoacoustic regime the energy conversion efficiency (optical to acoustical) is proportional to the energy of the pulse, optical absorption saturation must be produced at some point. As an example and without loss of generality, we assume that the optical absorption coefficient μ_a as a function of the optical energy of a single pulse $E_{o,1}$ can be approximated as

$$p_0 = k\frac{1}{{E_{o,1}}^{\alpha}}\ , \quad (5)$$

being k a constant and α an arbitrary number. Fig. 2a represents μ_a as a function of optical energy for α=1 and α=2. The time profiles of the optoacoustic signals generated by a tone-burst of 3 pulses for α=1 and α=2 are displayed in Fig. 2b along with the signal generated with a single pulse with the same energy for $E_{o,1}$=1 (a.u.). The corresponding frequency spectra are shown in Fig. 2c. It is shown that the amplitude spectral density of the signals generated with a tone-burst can be higher than for the signals generated with a single pulse if optical absorption saturation is produced.

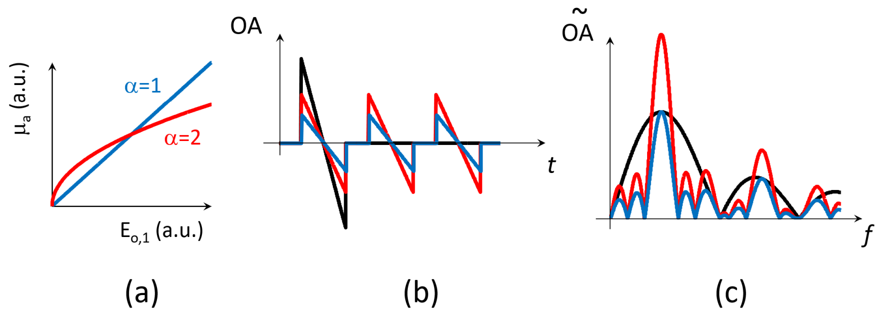

Figure 2: Comparison of the optoacoustic signals generated by a spherical absorber with single-pulse and tone-burst (3 pulses) excitation when optical absorption saturation takes place. (a) Optical absorption coefficient as a function of the energy of the laser for α=1 (blue) and α=2 (red) in Eq. (5). Time profiles of the pressure signals for single-pulse (black) and tone-burst (red) excitation with the same energy for α=1 (blue) and α=2 (red). (c) Amplitude of the Fourier transforms of the profiles in (b).

Another non-linearity that can affect optoacoustic signal generation with tone-burst excitation is associated to the temperature dependence of the Grueneisen parameter. Light absorption from the first pulse of the burst causes a temperature rise that is proportional to the energy of the pulse. If the second pulse is emitted before the tissue relaxes to the original temperature, the generated optoacoustic signal has a larger amplitude. This effect is repeated for subsequent pulses. Fig. 3a displays the temperature profiles in the excited tissue for a tone-burst of 3 pulses featuring an inter-pulse separation smaller than the thermal relaxation time. The time profiles of the optoacoustic signals generated under these conditions for single-pulse and tone-burst excitation are shown in Fig. 3b. The corresponding frequency spectra are shown in Fig. 2c. Again, it is shown that the amplitude spectral density of the signals generated with a tone-burst can be higher than for the signals generated with a single pulse if the temperature rise is sufficiently high.

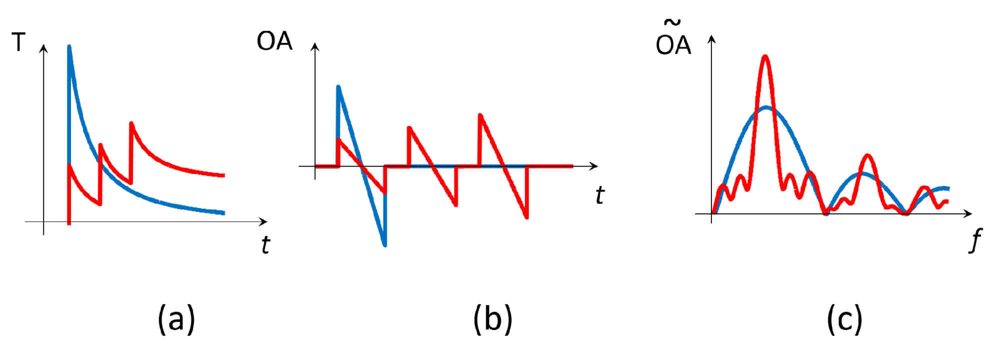

Figure 3: Comparison of the optoacoustic signals generated by a spherical absorber with single-pulse and tone-burst (3 pulses) excitation when a temperature rise is produced. (a) Temperature time profiles for single-pulse (blue) and tone-burst (red) excitation for an inter-pulse separation shorter than the thermal relaxation time. (b) Time profiles of the pressure signals for single-pulse (blue) and tone-burst (red) excitation. (c) Amplitude of the Fourier transforms of the profiles in (b).

4. DISCUSSION AND CONCLUSIONS

In general, it is expected that the linear relationship between the optoacoustic pressure and the optical energy is maintained for nanosecond duration pulses with energies below safety limits. Thereby, tone-burst excitation is expected to generally provide lower SNR. However, if the energy of the tone burst is higher than for the single pulse, a higher SNR could be provided. It was shown herein the energy that can be delivered when conforming to safety exposure limits can be substantially increased for tone-bursts of low frequency. This may be of particular relevance for air-coupled transducers, which provide the unique advantage to enable non-contact optoacoustic imaging of arbitrary samples but can only operate at low frequencies with reduced sensitivity [17]. Tone-burst excitation may also play a role in optical resolution microscopy where the non-linear effects discussed herein have been detected [18]. By exploiting the temperature dependence or the signals or optical absorption saturation it may be possible to enhance the contrast and resolution of the images. Another potential application of tone-burst excitation is to measure blood flow based on the Doppler effect. Doppler optoacoustic imaging is hampered by the broadband nature of the signals. Reducing the bandwidth of the signals with an intensity modulated source based on a sinusoidal function of finite length has been shown to enable detecting frequency shifts associated to the flow velocity, and tone-burst excitation based on a train of equally-delayed pulses can also serve this purpose [12].

In conclusion, while the optoacoustic signals generated with a tone-burst based on a train of equally-delayed pulses generally have lower signal-to-noise ratio than those excited with a single pulse, some cases can be identified where the amplitude spectral density can be higher with tone burst excitation. Thereby, this excitation approach can become the method of choice for enhancing optoacoustic contrast in some applications.

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